El Niño, the 2006 Indonesian peat fires, and the distribution of atmospheric methane

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Received 8 July 2013; revised 3 September 2013; accepted 6 September 2013.

[1] Dry conditions from a moderate El Niño during the fall of 2006 resulted in enhanced burning in Indonesia with fire emissions of CO approximately 4–6 times larger than the prior year. Here we use new tropospheric methane and CO data from the Aura Tropospheric Emission Spectrometer and new CO profile measurements from the Terra Measurements of Pollution in the Troposphere (MOPITT) satellite instruments with the Goddard Earth Observing System (GEOS)-Chem model to estimate methane emissions of 4.25 ± 0.75 Tg for October–November 2006 from these fires. Errors in convective parameterization in GEOS-Chem, evaluated by comparing MOPITT and GEOS-Chem CO profiles, are the primary uncertainty of the emissions estimate. The El Niño related Indonesian fires increased the tropical distribution of atmospheric methane relative to 2005, indicating that tropical biomass burning can compensate for expected decreases in tropical wetland methane emissions from reduced rainfall during El Niño as found in previous studies. **Citation:** Worden, J., et al. (2013), El Niño, the 2006 Indonesian peat fires, and the distribution of atmospheric methane, *Geophys. Res. Lett.*, *40*, doi:10.1002/grl.50937.

1. Introduction

[2] Recent studies suggest that wet tropical conditions from La Niña result in increased wetland emissions, whereas dry tropical conditions from El Niño result in decreased wetland emissions [*Hodson et al*., 2011], and that this El Niño/La Niña (or ENSO) driven variability could partly explain the recent methane increase since 2006 [e.g., *Dlugokencky et al*., 2009]. Variations in tropical fire emissions potentially counterbalance the change in emissions from tropical wetlands, as dry conditions resulting in decreased wetland emissions can be favorable toward increasing fire emissions [*Bousquet et al*., 2006; *Dlugokencky et al*., 2009; *Andreae and Merlet*, 2001]. Model-based methane estimates from fires can have large uncertainties because of the spatial and temporal variability of fire emissions, primarily derived from satellite-derived burnt area measurements, as well as the dependency of the fire CH_4/CO_2 emission factors (g/kg dry matter burned) on fuel type and combustion phase [e.g., *Van Der Werf et al*., 2010]. Furthermore, the resulting estimates of atmospheric methane from fires are not well corroborated by the surface network, primarily located in "background" locations where smoke plumes are typically diluted prior to measurement [*Dlugokencky et al*., 2009]. Reflected sunlight-based satellite measurements of atmospheric methane have not been used to quantify methane from fires because of scattering from aerosols in smoke plumes or sparse sampling of plumes [*Frankenberg et al*., 2011; *Ross et al*., 2013].

[3] During the fall of 2006, human-set fires and dry conditions from a moderate El Niño resulted in significant biomass burning emissions over Indonesia [e.g., *Field et al*., 2009] with CO emissions from the burning approximately 4–6 times larger than the previous year as discussed in *Logan et al*. [2008]. Here we use tropospheric CH_4 and CO measurements from the Aura Tropospheric Emission Spectrometer (TES) satellite instrument [*Worden et al*., 2012] along with new CO profiles, with near-surface sensitivity, from the Measurements of Pollution in the Troposphere (MOPITT) instrument and the Goddard Earth Observing System (GEOS)-Chem global chemistry and transport model to quantify CH_4 emissions from these fires and how the fires affected tropical tropospheric methane concentrations.

2. CH_4 and CO Distributions During the Fall of 2006

[4] Figure 1 shows the near-global distribution of methane and carbon monoxide in October 2006, observed by TES and simulated by the GEOS-Chem global chemistry and transport model (e.g., supporting information) [*Pickett-Heaps et al*., 2011]. Details on the quality flags, bias corrections, sensitivities, and uncertainties of the TES satellite data and comparisons to the GEOS-Chem model are discussed in the supporting information and in *Worden et al*. [2013]. In summary the CH_4 and CO data have approximately 1% or better precision and 0.5% or better accuracy after a constant bias correction is made to the data. These infrared-based estimates of methane have little sensitivity to aerosols from fires because aerosol optical depth from fires inversely depends on wavelength. GEOS-Chem model (2° × 2.5° spatial and 4 h time resolution) profiles corresponding to the best time and space match with each TES profile are used for the comparison. The TES-averaging kernels and a priori

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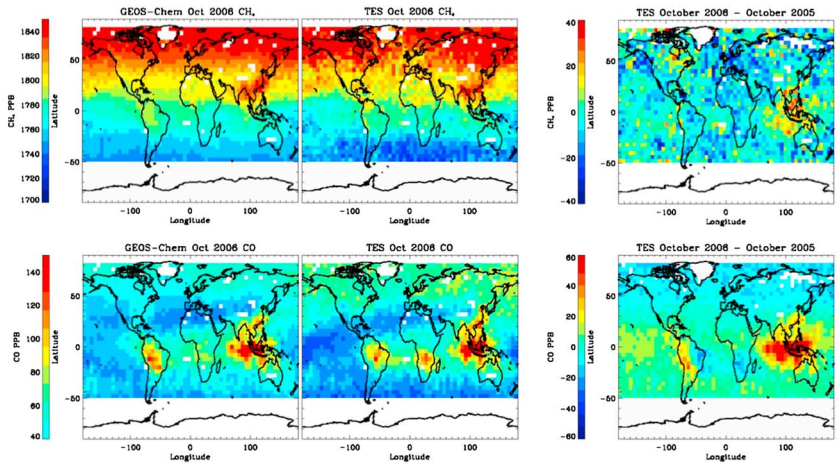

Figure 1. (top row) Methane estimates from the GEOS-Chem model, the TES data (for October 2006), and the difference between TES methane estimates in October 2006 minus October 2005. (bottom row) TES CO estimates corresponding to Figure 1 (top row). The map resolution is 2° latitude and 2.5° longitude.

GEOS-Chem model constraint are applied to corresponding GEOS-Chem model profiles to account for the TES retrieval regularization and vertical resolution. Although the TES IR data is primarily sensitive to methane in the free troposphere, the volume-mixing ratios of both model and adjusted TES profiles are then averaged over the whole troposphere to mitigate retrieval errors in the data and transport errors in the model. Figure 1 shows that the Indonesian fires make a clear impact on regional CO distributions, with observed enhancements up to 300+ ppb (see also Figure 2b). Because methane is long lived, the effect of the Indonesian fires on atmospheric methane is not readily apparent relative to the global distribution but can be observed by differencing the TES October 2006 and October 2005 CH_4 estimates (Figure 1, top right).

[5] Figure 2 (partly adapted from *Worden et al*. [2013]) shows model and data distributions of methane and CO for September, October, and November of 2006. A weighted least squares linear fit for the data distributions is calculated based upon TES observations errors. An empirical estimate of the "error" in the GEOS-Chem slope is calculated by the scatter in the GEOS-Chem distribution as discussed in *Worden et al*. [2013]. Based on in situ data [e.g., *Van der Werf et al*., 2010], we expect that an emission ratio near 0.11 (ppb/ppb) is representative of tropical fires, whereas larger values for the emission ratios indicate larger contribution from other sources (e.g., wetlands) relative to the emitted CO. *Worden et al*. [2013] (and supporting information) shows that this distribution is primarily explained by the Indonesian fire emissions. A larger slope during November indicates that the CH_4 emissions from the fires, relative to other sources, are lower. The larger scatter and lower correlation of the observed CH_4/CO data in September suggests that non-biomass burning sources contribute to the observed free tropospheric methane.

3. Estimate of Methane Emissions From Indonesian Peat Fires

[6] Previous efforts to reconcile satellite and model atmospheric composition estimates have been stymied by large uncertainties in the a priori model emissions and emission ratios, errors in modeled vertical transport, and the vertical sensitivity and uncertainties of the satellite data [e.g., *Kopacz et al*., 2010; *Liu et al*., 2010; *Jiang et al*., 2013]. For methane, disentangling the role of fire emissions from nearby wetland or anthropogenic emissions on observed atmospheric concentrations can also be challenging [e.g., *Bousquet et al*., 2006; *Worden et al*., 2013]. For these reasons, we use new methane data from TES (as well as CO to identify air parcels affected by the fires) along with new profile CO estimates from MOPITT to provide separate methane emission estimates from the fires and evaluation of these errors. optimal estimation (OE) is used to quantify emissions using these satellite data and the GEOS-Chem model. In the OE inverse framework, data and model are compared in a cost function that depends on errors in the data and prior knowledge of the emissions. Iterations of model emissions are performed until this cost function reaches a minimum.

[7] We first estimate total methane emissions from Indonesia for September, October, and November of 2006 using the TES data and the OE approach described in *Jones et al*. [2003] and supporting information. This approach quantifies emissions from large-scale land masses. Satellite data uncertainties and emissions from other sources are the dominant error terms calculated using this approach. These errors are random and therefore describe the precision of the estimate. We find total Indonesian fire emissions for the October through November 2006 time period are approximately 4.5 Tg ± 4% (Table 1 "Updated Biomass Burning" row), surprisingly consistent with the model estimate that is based on a burnt area estimate, the estimate of carbon from burnt area, and CH_4/CO_2 emissions ratios. However, the TES-based estimate depends on knowledge of the non-biomass burning Indonesian emissions (Table 1) and the errors on these emissions are not well known. The good agreement between model and data in the CH_4/CO distributions (Figure 2) indicates that we can evaluate the impact of this error by quantifying CO emissions. Errors in modeled vertical transport also directly propagate to the emissions estimate [e.g., *Jones et al*., 2003; *Kopacz et al*., 2010; *Jiang et al*., 2013]. To evaluate these two error sources, we provide a separate, corroborating estimate of the Indonesian biomass burning emissions and its errors using MOPITT multispectral CO profiles that can distinguish near-surface CO from free tropospheric CO (for land scenes

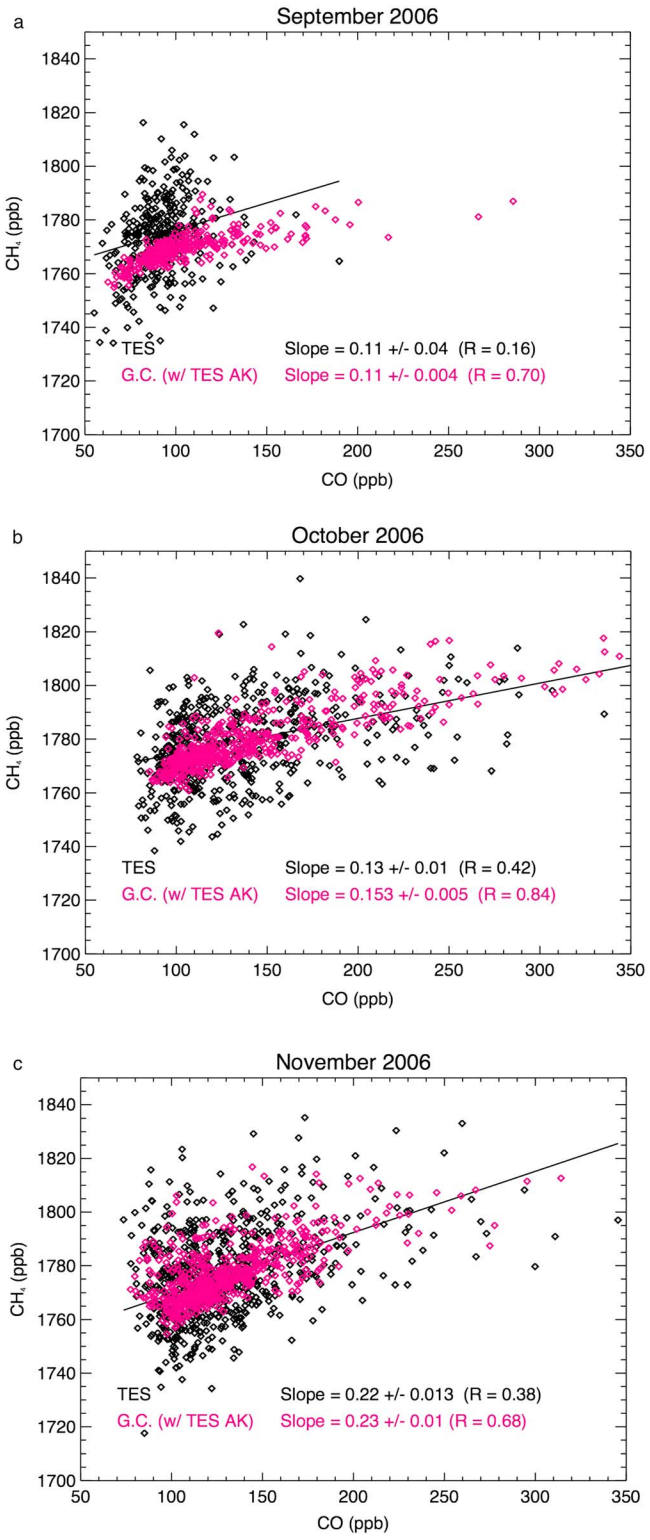

Figure 2. Observed (TES) and corresponding modeled GEOS-Chem distributions of CH_4 and CO over Indonesia (5°S to 15°N, 80°E to 130°E). The line is a fit through the TES data.

with less than 5% cloud contamination) and hence provide increased sensitivity to the fire emissions of CO and its subsequent vertical transport.

[8] We use a 4-D variational approach (supporting information) [*Kopacz et al.*, 2010; *Jiang et al.*, 2011, 2013] to quantify global CO emissions during the fall of 2006 using the MOPITT V5J profiles (supporting information) [*Deeter et al.*, 2013]. This approach allows for emissions estimates with substantially increased spatial resolution to take advantage of the near-surface sensitivity of the CO profiles for estimating the spatial variability of the fire emissions. However, precision errors are not calculated due to computational cost. Errors in modeled vertical transport affect the modeled vertical distribution of CO and hence CH_4. Emissions estimates based

Table 1. CH_4 Emissions Used for 2006 GEOS-Chem Model Estimates for September Through November 2006, Updated With TES CH4 Observations[a]

	Indonesia 2006 CH_4 Emissions			
	CH_4 (Tg/month)			
Emission Type	September	October	November	3 Month Total
A priori Total	2.39	4.06	1.67	8.12
A priori Biomass Burning	1.12	2.77	0.39	4.28
A priori Wetlands	0.67	0.69	0.68	2.04
A priori Other	0.60	0.60	0.60	1.80
Updated Total	2.23 ± 0.09	3.86 ± 0.09	2.24 ± 0.13	8.33 ± 0.18
Updated Biomass Burning	0.96 ± 0.09	2.57 ± 0.09	0.96 ± 0.13	4.49 ± 0.18
Updated CH_4 from CO	0.84	2.58	0.70	4.12

[a]The last row indicates the best methane estimate based on the MOPITT CO profiles.

Table 2. CO Emissions, Updated With MOPITT V5J CO Profiles and Columns

	Indonesia 2006 CO (Tg) Emissions			
Emission Type	September	October	November	3 Month Total
A priori	19.3	45.2	7.5	85.4
Update (CO Profiles)	13.7	42.3	23.4	79.4
Update (CO columns)	12.5	27.9	11.5	51.9

on the MOPITT CO profiles are therefore directly affected by errors in vertical transport. In principal, use of the MOPITT total column data to quantify emissions is less sensitive to vertical transport errors because the mass of the total column must be preserved in the model regardless of where convection places the corresponding air parcels. On the other hand, the MOPITT column-based estimates will preferentially weigh the CO values in the boundary layer over land, while over ocean, only the thermal channel contributes, with highest sensitivity in the midtroposphere [*Worden et al*., 2010]. We can empirically evaluate how the combination of vertical sensitivity in the satellite data and vertical transport error in the model affects the emissions estimates by comparing the results of the inversion using the MOPITT profile against an inversion using the total column. Figure 3 (left) shows the vertical structure of the mean relative bias across the tropics and subtropics, averaged from 20°S to 20°N, between the modeled and a priori CO fields (supporting information). The a priori shows a large positive bias in the middle troposphere corresponding to the equatorial Eastern Pacific Ocean, the Atlantic Ocean, and the Indian Ocean. These horizontal biases are due to continental outflow as discussed in *Liu et al*. [2010] and are significantly reduced in the a posteriori simulations with both the profile and column inversions. However, residual vertical gradients exist over all regions that are consistent with vertical transport biases in the model [*Liu et al*., 2010; *Jiang et al*., 2013] and which cannot be corrected in the inversion of the emissions.

[9] As shown in Figure 3, emissions estimates from the profile-based inversion have the smallest residuals between the MOPITT profile data and GEOS-Chem model for September and October. Both approaches yield acceptable results for November with the profile-based estimate biased high over Indonesia and the column-based estimate biased low. Using both results for November and the profile-based results for September and October (Table 2), along with the a priori emission ratio of 0.061 g/g (0.106 ppb/ppb) for CH_4/CO suggests a range of CH_4 emissions of 4.1 to 5 Tg (Table 1, "Updated CH_4 from CO" row).

[10] The uncertainty in the CH_4/CO emission ratio also affects this estimate. From *Andreae and Merlet* [2001] we expect an approximate 35% error in the CH_4/CO emission ratio for a single fire and consequently a smaller error when the fires are aggregated over region and a month. Although the observed and modeled CH_4/CO distributions (Figure 2) agree within the errors of the actual CH_4/CO ratio, the

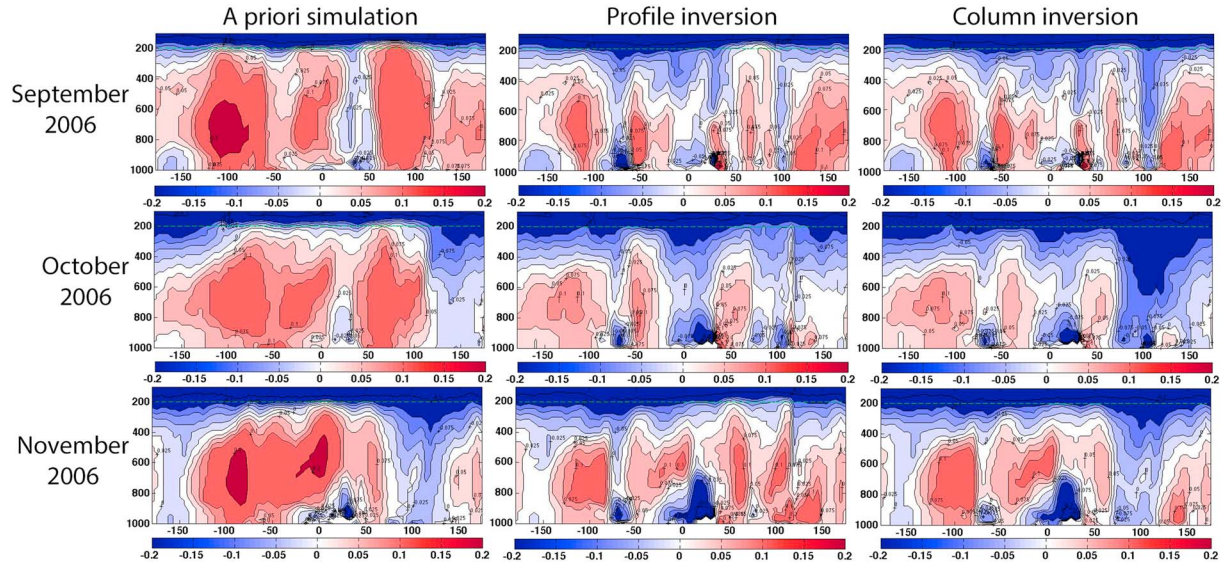

Figure 3. Fractional (color bar) residuals between Model and MOPITT CO profiles averaged between 20°S and 20°N. The *x* axis is longitude and the *y* axis is pressure (hPa). (left column) residuals before the (middle column) profile-based inversion and (right column) column-based inversion. Indonesia is near 110°E longitude.

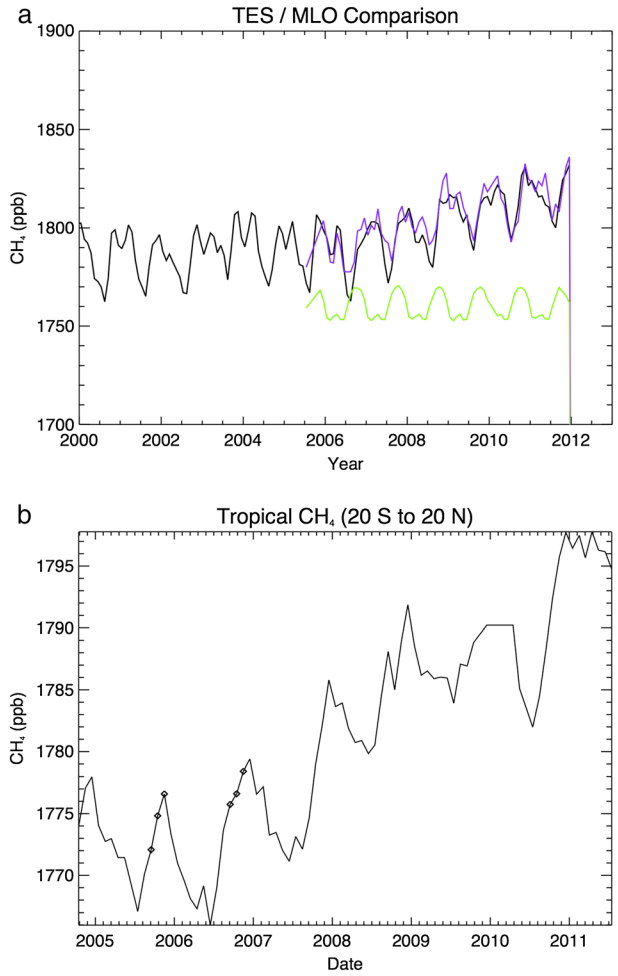

Figure 4. (top) Comparison of TES tropospheric methane 1000 km surrounding Mauna Loa surface data. The green line is the a priori used with the TES methane estimates. (Bottom) Time series of TES-measured tropospheric methane for all longitudes between 20°S and 20°N. The diamonds indicate the September through November time period for 2005 and 2006.

difference suggests that the model emission ratio could be biased low by 13% based on the October distributions in Figure 2. Assuming these errors are not random, the spread in the CH_4 estimate could range from 3.5 to 5 Tg, which spans the estimate using the TES CH_4 data. As discussed earlier, this range now incorporates the error terms from data, transport, and knowledge error in nearby non-biomass-burning emissions. For these reasons we report a value of 4.25 ± 0.75 Tg for these El Nino driven fires (Table 2).

[11] To our knowledge this is the first estimate of methane emissions from fires using satellite atmospheric composition measurements. This estimate is surprisingly consistent with the model-based estimate of 4.28 Tg that is based on burnt area index, estimates of CO_2 emissions from this burnt area, and in situ observations of CH_4/CO_2 emission ratios in tropical biomass burning plumes [*Andreae and Merlet*, 2001; *Van Der Werf et al*., 2010].

4. Summary and Implications

[12] Expectations are that wetland emissions should decrease during an El Niño year due to reduced rainfall and drying [*Hodson et al*., 2011; *Bloom et al*., 2012], and consequently, we might expect tropical and subtropical atmospheric methane concentrations to decrease between 2005 and 2006. However, both TES and the NOAA data near or at the remote Mauna Loa site (Figure 4) show that atmospheric methane concentrations remained approximately constant between 2005 and 2006, whereas TES data show that free tropospheric methane increased in the tropics by about 2 ppb. As seen in Figure 1, the Indonesian region is the only tropical region with a significant excess of methane, whereas methane concentrations over other tropical and subtropical wetland regions in Africa and South America showed either no change or slightly lower concentrations as might be expected during an El Niño year [*Hodson et al*., 2011]. Emissions from these human-set fires, amplified by a moderate El Niño, therefore, compensated for decreasing emissions elsewhere in the tropics to increase tropical tropospheric methane concentrations as observed by TES. We conclude that changes in wetlands and fires must both be quantified when examining the effects of ENSO variability and expected drying in a warming climate [*Neelin et al*., 2006] on atmospheric methane.

[13] **Acknowledgments.** Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Work at the University of Toronto was carried out with support from the Natural Sciences and Engineering Research Council of Canada. The Mauna Loa data in figure was provided by the NOAA ESRL website. The NCAR MOPITT project is supported by the National Aeronautics and Space Administration (NASA) Earth Observing System (EOS) Program. The National Center for Atmospheric Research (NCAR) is sponsored by the National Science Foundation.

[14] The Editor thanks two anonymous reviewers for their assistance in evaluating this paper.

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